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MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

OCEANOGRAPHIC AND METEOROLOGICAL RESEARCH

FIRST REPORT OF THE ADVISORY COMMITTEE

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OCEANOGRAPHIC AND METEOROLOGICAL RESEARCH IN RELATION TO SEA DEFENCE

FIRST REPORT OF THE ADVISORY COMMITTEE ON OCEANOGRAPHIC AND METEOROLOGICAL RESEARCH

To: The Rt. Hon. Christopher Soames, C.B.E., M.P.,
The Minister of Agriculture, Fisheries and Food.

A. INTRODUCTION

1. Coastal flooding will occur when the level of the sea exceeds a known danger level which varies from place to place along the coast. Under normal conditions of tide this danger level will be approached at some places several times during an average year, especially near the spring and autumnal equinoxes when the largest tides normally occur. These tidal levels can be greatly increased by what is known as a storm surge; that is an abnormal rise of sea level caused by strong winds, and to a lesser extent by their associated barometric effects. The height of a storm surge, which may reach ten feet or more in extreme cases, varies in accordance with many conditions, such as the depth of water and nature of the coastline, and may frequently suffer considerable change inside estuaries. Conditions of special danger can occur when the surge is at a maximum at or near the time of local high tide. On some occasions, as in the disastrous floods of 1953, the dangers of flooding are also increased by severe wave action.

2. Following the Thames floods of January 1928 certain studies were made of the factors which might lead to flooding. In particular, the formation of surges in the North Sea was studied by the Liverpool Observatory and Tidal Institute. The meteorological conditions which lead to surges were studied by the Meteorological Office. The 1953 floods emphasised the urgent need for further researches of this character.

3. In order to co-ordinate the research work which appeared necessary, the Advisory Committee on Oceanographic and Meteorological Research was appointed in July, 1954 by the then Minister with the following terms of reference:-

> 'To co-ordinate the research work on oceanographic and meteorological matters in relation to sea defence, recommended in Appendix B of the Report of the Waverley Committee on Coastal Flooding, and to advise the Minister of Agriculture, Fisheries and Food on any related matters which might be referred to them from time to time'.

Details of membership are given in Appendix 1 to this report.

4. The Committee first met in October, 1954. Since that time meetings have been held about twice a year. The Committee has co-ordinated the researches recommended in Appendix B of the Waverley Report and has considered other problems which have been referred to it from time to time. The researches recommended in the Waverley Report are as set out in Appendix 2 to this Report.

5. Research work has been carried out on behalf of the Committee by the Government Departments concerned and by the University of Liverpool Tidal Institute and Observatory (formerly the Liverpool Observatory and Tidal Institute) and the National Institute of Oceanography. The grants set out in Appendix 3 to this Report have been paid to these Institutes by the Ministry of Agriculture, Fisheries and Food to meet the costs of the work.

B. IMPROVEMENTS TO THE EAST COAST FLOOD WARNING SYSTEM

General Description of the System

6. In their Interim Report of July, 1953, the Waverley Committee strongly advocated the early establishment of a flood warning system for the East Coast. Their recommendations were accepted, and the Flood Warning Organisation came into operation on 15th September, 1953, and has since operated each winter from about the middle of September to the end of April. The technical centre of the warning service has been conveniently located with the Central Forecasting Office of the Meteorological Office, first at Dunstable and later at Bracknell. Flood Warning Officers have been supplied by the Hydrographic Department of the Admiralty. Administrative responsibility for the service rests with the Ministry of Agriculture, Fisheries and Food.

7. Although the practical operation of the Flood Warning System is not within the terms of reference of the Advisory Committee, it is thought that a brief account of the System and the improvements made will be of interest and will serve to show the background against which the research has been undertaken.

8. The System relies on meteorological reports, and information on observed tidal heights at Aberdeen, Tyne, Immingham, Lowestoft and Harwich. Originally Leith was included and Stornoway has recently been added. (See paragraph 13). The transmission of tidal data to the Duty Officer is arranged in collaboration with the Meteorological Office. The local harbour authorities pass the tidal heights by public telephone to the nearest Meteorological Office Outstation when so ordered by the Duty Officer and in accordance with a system which allows for such reports to be sent at frequencies ranging from once daily in calm weather to a maximum of every hour when surges are present. The local Meteorological Office Outstation passes the data through a Meteorological Office Group Station to the Central Forecasting Office by teleprinter.

9. The Flood Warning Duty Officer compares observed tidal heights with predicted heights, and so plots the progress of a surge as it moves down the East Coast. If it appears that danger levels are likely to be reached the Duty Officer sends warnings to the river boards and police authorities in the areas affected. The police are responsible for passing on messages to local authorities and the public as appropriate.

10. Warning messages up to April, 1962 have been classed either as 'Amber' or 'Red'. The Amber warning, issued about 12 hours before the time of local high water and based on meteorological information, indicates that a surge is likely to develop. The Red warning is sent when tidal information from the northern ports enables an assessment to be made of the size and time of arrival of the surge. It is issued about 4 hours before local high water. The Red warning messages include an estimate of the height of sea level at the next high water and also a local wind forecast. Both types of message are cancelled when the danger has passed. For the purpose of issuing warnings the East Coast of England was divided. In each division a port was selected and a danger level agreed which represented the level at which there might be danger of flooding somewhere in that division.

Changes in Practical Aspects of the System

11. The Flood Warning System has been kept under continuous review since its inception in September, 1953. As sea defences were improved, danger levels were adjusted in consultation with the river boards. To take account of local variations in danger levels, it was found desirable to increase the number of divisions on the East Coast of England from four to six. The southernmost division was divided into two because some of the Kent coast defences were shown to be six inches lower than the defences were shown to be six inches lower than the defences in the remainder of the division. Similarly the division covering Yorkshire, Lincolnshire and East Anglia was divided into two because the danger level for the agreed key port, Immingham, was not suitable for the area round the Wash, where northerly winds often caused surge heights to be larger than those in the Humber. The tide-reporting station at Leith was dropped from the System as it was found that the tidal data obtained from it were of little or no value.

12. More recently a change was made in the procedure for Amber Alerts, so that when these remained in force up to the time of high water it would be understood that the level was expected to reach within six inches either side of danger level. This new procedure removed the need to issue Red Alerts when really dangerous surges were not expected. It was subsequently agreed that if an Amber Alert was in force at four hours before high water in any division it would then be either confirmed, cancelled or substituted by a Red Alert. Addressees were thus assured that no message had been missed.

13. More accurate surge forecasting becomes possible as progress is made on the programme of installation of tide gauges, discussed more fully in paragraphs 36 and 37 below. In particular, the recent arrangements for the reception of tidal data from Stornoway as an additional reporting station should in the future provide positive evidence of the formation of an external surge. Previously, the first intimation of a surge came from Aberdeen.

Studies by the Flood Warning Officers

14. As time has permitted, the Flood Warning Officers have carried out a considerable amount of practical research, such as the examination of the speeds of associated depressions, the effect of local winds on surges in particular localities, the study of the changes in surge heights caused by estuaries, e.g. the Humber, and the analysis of records of previous surges. The storm of 21st to 23rd December, 1954, and the resulting surge, which was the largest since the 1953 floods, was studied in detail by a Meteorological Office forecaster and one of the Flood Warning Officers.

15. Consideration has been given to the possibility of danger levels being reached in the summer months. A flood warning system had not been considered necessary in the summer, because records for the past twenty-five years showed that dangerous levels had never in fact been reached during the months May to August. However, the Flood Warning Officers thought it adviaable to re-open the investigation following a surge which occurred in July, 1961, and the question of extending the period of operation of the Warning System is under consideration.

Statistics on the Frequency of Exceptionally High Levels

16. The Waverley Report drew attention to the advisability of preparing, from the existing tide gauge records for certain ports, statistics on the frequencies at which certain high water levels had been reached over a period of years. Studies have therefore been made of past high water levels at certain ports An upper limit can be placed on a tidal height but not on a surge height. It follows that no upper limit can be fixed for the maximum possible combination of tide plus surge. The only practical way to provide estimates of maximum levels is by probability investigations and these have been conducted for all stations around the British Isles where sufficient reliable tide gauge data have been found to exist.

17. The work of the Tidal Institute on maximum levels on the West Coast is reported in paragraph 34 below. The Flood Warning Officers have examined the tidal records at ten ports on the East and South Coasts for periods ranging from twenty to more than

fifty years. Details were extracted of the number of occasions on which various levels had been exceeded, starting somewhat above the height of the highest predicted tide and increasing by steps of six inches. From these data figures were obtained of the frequencies of occurrence of various heights at each port, increasing by steps of six inches up to the highest level recorded. The results showed that:-

(a) at each port, the frequency with which a level was surpassed diminished approximately by the same factor for each increment of six inches in the level;

(b) the factor was not the same for all coasts, being about a half for ports on the East Coast of England, but nearer a quarter for ports on the South and West Coasts. For example, whereas at Southend a height of 12.0 ft. had been exceeded about once every two years on the average, 12.5 ft. about once every four years, and so on, at Southampton 8.0 ft. had been exceeded about once every two years, and 8.5 ft. only about once every eight years etc.;

(c) the levels reached at the East Coast ports on the night of 31st January/1st February, 1953, by extrapolation from the frequency of occurrence of lower heights, appeared likely to occur only about once every century or two.

18. Owing to the infrequency with which really high levels have been reached during the comparatively short periods for which accurate tidal records have been kept at most ports, the extrapolation referred to at 17(c) above was far from satisfactory. Hence a new approach to the problem was tried by using the statistical theory of annual maximum heights, whence the frequency of occurrence of extremely high levels could be deduced more accurately. It was found that this theory, which had not previously been applied to tidal heights, was applicable to them and gave results which, when extrapolated to periods of the order of one-hundred years, appeared to be more reliable than the earlier method - though still consistent with the earlier results.

19. Briefly, the method consists of extracting from the tidal records of each port the maximum height reached in each year for

as far back as possible. A theoretical curve is then fitted to the frequency distribution of these observed annual maxima and can be extrapolated with reasonable confidence to give an estimate of probabilities over fifty to one hundred years. One major difficulty was, however, encountered when dealing with the East Coast ports. This arose because the annual maxima for these ports have had a marked continuous upward trend for the past fifty years or so, at the rate of the order of a foot per century. This upward trend was only apparent in the records for the ports studied on the East Coast, but was not apparent at any ports on the West Coast or at Portsmouth or Southampton, although it did appear at Newhaven. Only one port in the area has records going back for over one hundred years (with gaps unfortunately), namely Sheerness. From the records there, it appears that this steady rise in the annual maximum levels has not been continuous throughout the hundred years. Up to about 1910, when the rise mentioned above at all the East Coast ports seems to have begun, the annual maxima for Sheerness rose for perhaps a dozen years and then fell again. There appears to be no continuous trend either up or down for more than fifty years.

20. This possible rise in the maximum levels reached by the sea appears to be tied up with an observed rise, relative to the land, of the mean level of the sea in the southern part of the North Sea, which is clearly apparent in the records for Sheerness. The relative levels of sea and land can only be decided by computation of the values of mean sea level for as many ports as possible for as many years as possible, which involves a considerable amount of laborious calculation. The Ordnance Survey are undertaking this work, and other bodies are assisting. (The changes in mean sea levels are discussed more fully in paragraphs 38 - 40 below.)

21. The East and South Coast ports whose records, mostly going back for fifty years or more, have been studied are King's Lynn, Harwich, Southend, Tilbury, North Woolwich, London Bridge, Sheerness, Newhaven, Portsmouth and Southampton. In general the highest level recorded (which, for the seven East Coast ports, occurred on the night of 31st January, 1953) approximated, within a few inches, to the level that the theory indicated had a chance of one in a hundred of occurring in any year.

Formulae for Forecasting Storm Surges

22. The Tidal Institute has attempted to provide formulae of practical use to the Flood Warning Organisation in forecasting storm surges at the major ports on the East Coast. These formulae have been obtained largely by statistical methods but to be efficient such methods must be based on a sound physical understanding of the various phenomena observed. Thus an analysis of storm surges in the North Sea and of tidal records for the ports forming an essential part of the Warning System were prerequisites for the formulation of the statistical problem.

23. From studies of the water levels observed at many stations around the coast, and after removing the contributions to these levels by the normal astronomical tide, it has been possible to deduce, qualitatively, the major factors governing the height and timing of storm surges within the North Sea. Three of these factors have been examined in detail and allowance has been made for them in each forecasting formula. Two of the three factors, i.e. the effect of wind stress on the surface of the sea and the effect of barometric pressure, are discussed in detail in paragraphs 41 - 52 below. The third factor is the character of the surges observed in the North Sea.

24. The outstanding type of surge in the North Sea is the solitary wave travelling down the East Coast, and generated externally to the Sea, generally in the Atlantic to the North and West of Scotland. This is known as the 'external surge'. Another type, similar in effect, but different in origin is the 'return surge'. This is the result of water previously expelled from the North Sea by southerly winds, returning again as a travelling wave down the coast.

25. Both these travelling surges are of great importance on the East Coast of England, and neither has yet been adequately represented in terms of wind and atmospheric pressure. They can, however, be forecast, by relating their size and time of occurrence at any port on the East Coast to their size and time of occurrence at Aberdeen, or even further to the North-west. Thus, by including observations of surges at Aberdeen in the forecasting formulae, external and return surges can be allowed for down to the southern

end of the North Sea and even into the English Channel. In this way formulae have been obtained for Tynemouth, Immingham, King's Lynn, Lowestoft, Southend and Newhaven.

C. THE EFFECTS OF ESTUARIES, IN PARTICULAR THE THAMES, UPON EXCEPTIONALLY HIGH TIDE - CUM - SURGE LEVELS

26. The Tidal Institute has devoted a considerable amount of study to this particular aspect of the propagation of tides and storm surges as part of their work on the 'interaction between tide and surge'. 'Interaction' implies that tide and surge cannot be considered as being totally independent of one another, despite their totally different origins. The circumstances conducive to the development of interaction are found in shallow water. The problem has been considered as that of explaining the observed preference that storm surges in the Thames display for contributing their maximum effect, be it positive or negative, on the rising tide.

27. In addition to emphasising the intrinsic difficulty of this mathematical problem, attempts to obtain formal mathematical solutions have shown that while certain qualitative results could be obtained to confirm the existence of interaction, and even to give an order of magnitude in certain cases, an exact numerical solution for the ease of a natural estuary would still be required. In the hope of making further progress towards this end, a mathematical model has been designed which crudely represents the Thames and, using an electronic computer, solutions have been obtained for the propagation of different typical combinations of tide and surge from the North Sea into the Thames.

28. The results of the computations were found to agree remarkably well with the phenomenon as found in the Thames. It was found that the presence of a surge had a marked effect upon the rate of propagation of the tide up the estuary. Equally, the presence of the tide had a marked effect upon the rate of propagation of the surge up the estuary, and these two circumstances conspired to ensure that surge peaks occur most frequently on the rising tide. In other words, this is the physical explanation why surges in the Thames tend to avoid high water. This investigation has shown that a more detailed mathematical model of the Thames should be highly rewarding and

work is in progress on this. Moreover, it has emphasised that for many British ports the interaction between tide and surge requires future attempts to prepare more accurate surge forecasting formulae to be based on the idea of forecasting total levels. This requires further research by means of mathematical models and electronic computer techniques.

29. To assist the Flood Warning Organisation to obtain a clearer picture of the manner in which a very high level could be expected to be propagated into and along the Thames, the Tidal Institute carried out a statistical investigation, based on observed tide gauge readings of high water heights. These readings, in fact, refer to the tide plus surge. The results show the maximum level that can be expected at certain points along the Thames in terms of the maximum level observed at Harwich. They should enable the Flood Warning Organisation to apply, in their practical task, and on the basis of observations, some of the features of propagstion of tide and surge in the Thames that were brought out in the work on the mathematical model mentioned in paragraphs 27 - 28 above.

D. THE NEEDS AND POSSIBILITIES OF DEVISING FLOOD WARNING SYSTEMS FOR AREAS OTHER THAN THE EAST COAST.

30. The needs and possibilities of extending the operations of the Flood Warning Organisation to other coasts than the East Coast have been reviewed.

The South Coast

31. For the South Coast the need of a flood warning system has not been apparent, and only one investigation into the nature of surges along this Coast, and the possibility of forecasting them has been carried out. It has been found that surges in the English Channel can arrive from its western approaches, but are largely concentrated on to the French Coast by the rotation of the earth. Most of the surges recorded at Newhaven were found to have been propagated from the North Sea through the Strait of Dover, and a simple law relating the height and time of occurrence at Newhaven to that at Lowestoft was found to explain the majority of cases considered.

The West Coast

32. The need for a warning system for the West Coast has been the subject of considerable discussion. In consequence, the Tidal Institute has devoted a good deal of time to studying surges at Liverpool and Avonmouth. On the West Coast travelling surges, such as those found on the East Coast, cannot be observed before they become dangerous, so that forecasts of surges must be made solely on the basis of meteorological data. Applications of the correlation techniques used successfully for the East Coast, when applied to surges at Liverpool and Avonmouth, in many cases failed to give adequate representations of the observed disturbances, particularly when the growth and decay of the phenomenon was rapid. This feature was most noticeable in the Bristol Channel where the anomalies between observed and computed surges took the form of an oscillatory component. Further investigations led to a method of representing these important short period oscillations in a relatively simple manner. Unfortunately forecasting is not at present a practical proposition because the time lag between the wind and resultant surge is so small that extremely precise meteorological forecasting is necessary.

33. Another investigation has shown that major storm surges experienced on the West Coast are invariably associated with the rapidly changing wind fields which occur when certain secondary depressions travel eastwards from the Atlantic and achieve a near-resonant speed in their progression over the shallow waters of the Continental Shelf area. This has led to efforts designed to identify such potentially dangerous meteorological situations, in so far as they affect Avonmouth and Liverpool, using their tracks and other easily defined characteristics as criteria. This investigation has met with considerable success and tests conducted upon past surges, together with more recent disturbances experienced along these shores, suggest that this technique could give a forewarning of the occurrence of major surges of the order of 5 feet or more in magnitude and that sufficient indication of timing could be given to decide whether any particular high water at a West Coast port is likely to receive a significant contribution from the surge. Experience has indicated that other smaller surges associated with rapidly travelling wind fields can be treated by an extension of the method. Unfortunately not all West Coast storm surges are associated with rapidly moving barometric systems and the fact that surges which fall into other

categories are much smaller in magnitude, may be of little consolation if one considers the possibility of their coincidence with the high water of a spring tide. It should, however, be noted that surges generated by more stable meteorological circumstances have been found to be much more amenable to the application of the correlation techniques referred to in paragraph 32 above.

34. It is clear that the special problems presented by the West Coast will require a great deal of intensive study if all the physical forces significant to storm surge generation in this area are to be adequately represented in a forecasting formula. Consideration has been given to the fact that incursions of the sea, of the order of the East Coast disaster of 1953, are unknown in the West in recent history. It is true that reasonably reliable local records can be found which relate to the overtopping of sea defences, but in general these phenomena are so poorly documented that it is very difficult to assess the scale of the problem. For this reason it was considered advisable to devote some effort to attempts to assess the adequacy of existing coastal defences. Thus it is hoped that clear guidance will be given for the direction of future research into those channels which offer the most practical benefit to the community. In this connection an investigation of the frequency of abnormal levels was undertaken for the eleven ports on the West Coast and two on the East Coast of Ireland for which observations were available. These ports were Newlyn, Avonmouth, Cardiff, Swansea, Llanelly, Newport, Liverpool, Preston, Fleetwood, Heysham, Silloth, Belfast and Dublin. A number of established statistical techniques for the treatment of maxima were found to be inadequate for the characteristic distribution of the abnormal levels recorded on this Coast. Nevertheless it was found possible to establish the levels most likely to be attained once in one hundred and once in two hundred years. The stage has now been reached where the optimum height of sea defences has been defined in this way and is available to the authorities concerned. The adequacy of the existing sea defences can therefore be assessed and a proper indication given of the way in which more concentrated attention can be most fruitfully directed.

35. Both directly and indirectly the various aspects of research reviewed above have given assistance to authorities of

varied interests and particularly to coastal engineers. It is unfortunate that the investigations have been hampered by lack of data of sufficient duration and accuracy but it is considered that further work of great value in future years will be possible as records become available from the tide gauges being installed around the British Isles under the supervision of the Advisory Committee. Meanwhile the provisional technique which aims at the identification of potentially dangerous meteorological conditions, outlined in paragraph 33, can be held in reserve and with further development could provide the basis for an interim warning procedure should the need arise.

E.. TIDE GAUGES

36. Surges of the type that occurred in 1953 are fortunately rare, but their infrequency does not detract from their potential gravity. It is therefore important to base investigations on the longest possible period. A limiting factor in the early days of the Warning System was the lack of reliable tidal records covering a sufficiently long period. The Waverley Committee suggested a number of additional places at which tide gauges should be installed for the purposes of oceanographic research. To meet this problem the Ministry of Transport, with the support and advice of the Committee, has carried out a programme of installing new tide gauges and improving existing gauges. New gauges have also been installed at a number of Admiralty dock-yards by the Hydrographic Department of the Admiralty. The selection of suitable sites for tide gauges has presented a number of problems. If the records obtained from them are to be of value the gauges must be installed in positions on jetties or piers where the extremes of both high and low water levels can be recorded. The sites must be easily accessible from the land for an operator to maintain the instrument and change the charts as necessary. The recorder itself is a delicate mechanism and has to work under the most severe weather conditions. It must therefore be protected if reliable records are to be secured. With the co-operation of the harbour authorities and the manufacturers of tide recorders it has been possible to overcome most of these difficulties. Progress to date on the tide gauge programme is set out in Appendix 4 to this report.

37. The accurate reading of tide gauges and the rapid communication of data to the Flood Warning Office are essential for the operation of the Flood Warning System. It is therefore important to eliminate errors in reading gauges and to keep to the minimum the time taken in transmitting messages. With these objects in view it has been decided to introduce automatic distant reading tide recorders. These instruments will operate direct from the mechanism of the tide gauge and, making use of a direct G.P.O. telegraph line, will provide the Flood Warning Office with a continual record of tidal heights at the port concerned. As the equipment is costly, pilot schemes are being carried out at Aberdeen and Immingham. If these schemes are successful it is proposed to introduce similar improvements at other ports supplying information to the Flood Warning Organisation. By these means it should be possible to issue warnings about thirty minutes earlier than at present, and to eliminate errors in the reception of tidal data which could lead to false alarms or the failure to issue warnings when they are in fact warranted.

F. LONG-TERM CHANGES OF MEAN SEA LEVEL RELATIVE TO THE LAND

38. The Advisory Committee has attached great importance to the long-term changes in the relative heights of land and mean sea level, and in 1958 they appointed a Sub-Committee on Mean Sea Level with the following terms of reference:-

(a) to advise on the provision, collection, reduction and dissemination of data relating to mean sea level round the British Isles;

(b) as required by the Advisory Committee on Oceanographic and Meteorological Research to advise and make recommendations regarding the provision of data necessary to enable mean sea level to be determined, in particular on the setting up and operation of tide gauges and carrying out of spirit levelling.

39. The main practical importance of mean sea level in relation to storm surges arises from its influence upon the probability of occurrence of dangerous levels. In the Thames Estuary, for example a rise in mean sea level of half a foot would mean the doubling of the probability of any given danger level being reached. From this

point of view, if from no other, estimates of changes in mean sea level are of great importance. They can only be obtained from long series of good observations recorded by tide gauges at many points around the coast. A network of gauges of the required density has not previously existed for the British Isles, and hence the estimates that can be made of secular changes are of a somewhat doubtful nature and confined to only a few places. However as a general guide it can be said that relative to the land, sea level is rising in the South of England at a rate of the order of half a foot per century. Taking the evidence of tide gauges over the whole of the globe there is a general tendency for the total volume of sea water to be increasing, and hence there is a general rise in sea level relative to the land.

40. It might be thought that a rise of this order is not of tremendous importance, but it has a bearing on the policy of constructing permanent sea defences, for if this rate were maintained for a century, the probability of high levels being reached would be much increased. It is extremely unlikely, however, that this rise will remain constant. An increase in mildness in world climate such as has been experienced in the distant past, could result in a considerable acceleration in the rate of rise. On the contrary, the rise could equally well be reversed in the future, into a fall of sea level relative to the land. More precise conclusions can only be arrived at after the tide gauge network now being installed around the British Isles has produced the data for which it is intended.

G. BASIC RESEARCH

41. The National Institute of Oceanography has studied the response of the sea surface to the wind and atmospheric pressure and the free and forced oscillations that are possible in the North Sea. These are essentially basic studies aimed at explaining the events that lead to unusual water levels. Early work included measurements of change in wind speed and direction relative to height above the surface of the sea to find out how much of the wind energy goes into the water under different conditions. These early results were checked on a broader scale against measurements of the slope of the surfaces of large lakes and reservoirs under the action of the wind. We still have

nothing like a complete understanding of all the factors involved, and no opportunity is missed of obtaining further evidence.

42. Some progress has been made by studying the effects of the wind on the flow of water through the Strait of Dover. This indicates that the wind drag is somewhat greater than over still water, and there is a clear indication that the same wind strength (measured at customary heights above the surface) is more effective in Winter than in Summer. The findings include surges of current which lag up to six hours behind the time of the strongest wind. Consideration of the effect of the wind at the surface has been strengthened by simultaneous studies of the effect of friction at the bottom of the sea. Further relevant information has been obtained from simultaneous wind and current observations from a number of lightships in the North Sea.

43. Another problem, and one not capable of easy solution concerns the natural oscillations in the North Sea, i.e. whether the water in such a large irregular basin will swing in regular motion either as a whole or in sections if disturbed overall by changes of atmospheric pressure or wind. Examination of hourly heights of water at a number of coastal ports has given some indication of variations in water level lasting thirty to fifty hours. but without the regularity determined by fixed size and shape. The observed changes are probably due to slow progressive waves taking about this time to move southwards, and there seem to be allied variations of about the same duration in the meteorological records. There seems to be no conclusive evidence of large natural oscillations apart from the tides. Useful progress has been made by theoretical study of the propagation of a long wave, such as might be produced by the wind acting on one half of a rectangular sea, into the other half not yet disturbed by the wind. This work has given a clear indication that such steady conditions would cause a change in level, partly steady and partly oscillatory, and that the rise of water level, measured from the first arrival of the disturbance, is likely to be more rapid, though smaller in amount, the farther it travels from the generating area. The work also suggests that at the greater distances the first rise of water level, i.e. the positive surge, is likely to be followed by a fall of water level or negative surge, or more than one. The reflection of surges by a barrier or by a coastline at an angle to the direction of propagation has also been studied.

44. Natural oscillations of the North Sea were also studied by the Tidal Institute in connection with its work on the preparation of forecasting formulae for East Coast ports. From an exhaustive study of large surges at Lowestoft the Tidal Institute was able to find only one particular meteorological situation for which oscillatory motion occurs. This is the situation which gives rise to a 'return surge' described in paragraph 24.

45. Comparison by the National Institute of Oceanography of the sea level changes with the variations in atmospheric pressure and wind has given a clear indication that the size of a surge depends on the rate at which conditions change as well as on the strength of the wind blowing down the North Sea. Theoretical study of the probable effect of surges entering the North Sea from the open Atlantic Ocean has shown that long waves (lasting an appreciable part of the day) which approach the British Isles from the West will be turned round the North of Scotland by the effect of the earth's rotation to travel southwards behind the land barrier in what would otherwise be a shadow zone. The height of the wave would be expected to decrease rapidly with distance from the coast, but near the coast it is likely to be considerably higher than the original wave coming from the open ocean. Further theoretical work has suggested that a second barrier like that presented by the continental coast of the North Sea will do little to modify this general conclusion.

46. To check these ideas it was necessary to have tide gauge records from the North and West Coasts of Scotland. Temporary gauges were erected at Lerwick and Stornoway and with the co-operation of the Harbour Masters concerned continuous records well calibrated in time and height have been obtained continuously over the past four years. To study the non-tidal effects, the predicted astronomical tides have to be subtracted from the observed levels. Three-hourly values of air pressure and wind from meteorological records for comparison with the non-tidal fluctuations were extracted with the help of the

Meteorological Office. The first result was clear confirmation of the overall barometric effect well-known for more than a century. (See footnote.)

47. Detailed analysis of three-hourly values of water level, atmospheric pressure and North-South and East-West pressure gradients over long periods at Lerwick and Stornoway show that variations in water level taking longer than a day are generally greater than the exact equivalent to the atmospheric pressure change. Shorter period changes in water level were further magnified in relation to the changes in atmospheric pressure. Analysis of the variations in pressure gradients showed that speed of propagation was as important as intensity. There is still much to do before results are available for practical use. There is some evidence of a 7½ day oscillation off the North-west Coast of Scotland that has nothing to do with air pressure variations or tides, and it seems to be about the period expected for a natural oscillation in a basin which has the size and depth of the North Atlantic Ocean.

The sea level goes down as the atmospheric pressure rises and goes up as the air pressure falls. The air and water are both fluids, and the underlying one has to adjust itself as well as it can to the distribution of pressure at its surface, to move away from regions of high pressure and to flow into those of low pressure. The inertia of the water, and geographical restriction of its flow as in narrow estuaries is likely to lessen the response of the water to atmospheric changes: water level at London Bridge, for example, will change only about seven inches to a change in atmospheric pressure of about one inch of mercury (equivalent to thirteen and a half inches of water), whereas in the deep ocean the change will be about thirteen and a half inches. The rate of change of the air pressure is a relevant factor, and under certain conditions the movement of the atmospheric disturbance may produce unique effects. It has been known for many years that a long wave, in which the wave length is much greater than the depth of water and of the scale of atmospheric disturbance, travels at a speed that depends only on the depth of water. Over the deep ocean an atmospheric disturbance cannot travel fast enough to keep pace with the long wave, but in coastal seas and the shallower parts of the continental shelf, less than 50 fathoms or so, it can advance at about the same speed as the wave it is making, so that there is a unique situation of near-resonance in which energy is continually fed to the wave, causing a large surge. It is something like the supersonic bang produced when an aeroplane flies so near the speed of sound that sound energy is accumulated. In varying depths of water, with the added possibility of resonant oscillations of harbours, inlets, bays and larger coastal regions when long-waves energy reaches them, the final situation may be really complicated.

48. To allow further progress the water level and meteorological data have been placed on punched cards so that all the computations can be done by an electronic computer. A method for analysing and predicting tides and for removing the tides from the water level observations has also been worked out for the computer. Observations from Malin Head obtained through the generosity of the Irish Ordnance Survey Office at Dublin are being included in the scheme.

49. Ever since the work started it has been clear that it would not be possible to apply the findings to the North Sea without taking detailed account of its irregular shape, bottom relief and variations in tidal depth. This would involve very extensive calculations and the National Institute of Oceanography decided to rely on an electronic analogue model in which the sea is divided into a number of squares in each of which the area, depth etc., are imitated by electronic components, and in which wind stress, pressure gradients, tide raising forces, effects of the earth's rotation, bottom friction, water level and velocity are imitated by voltages and electric currents. After several years work the model is now coming into use. It has given good agreement when tested against observations and calculations of the tides, and will soon allow a wide range of meteorological conditions to be reproduced and their effects studied in relation to the tide and other factors. The first experiment will be with the conditions that brought about the disastrous surge of 1953. Experience gained during the construction of the model will allow the method to be adapted very readily to other coastal areas when required. Its use for practical forecasting will then be tested.

50. Reference has been made in paragraph 27 to the use of an electronic computer by the Tidal Institute to obtain solutions for a mathematical model of the Thames. Such models can be designed to include the influence of bottom friction, variations in depth and breadth of an estuary, upland flow, the influence of atmospheric pressure and wind stress, and are suitable for investigations of tides, surges, or combinations of both. For the two-dimensional problem of a sea as opposed to the one-dimensional problem of an estuary, they can include the additional and extremely important influence of the earth's rotation. In this form they are analogous to modern methods of numerical weather forecasting, are complementary to the analogue model referred to

in paragraph 49, and offer an attractive prospect of treating the phenomena of tides and surges simultaneously over large areas. To link up with the detailed mathematical model of the River Thames referred to in paragraph 27, a larger mathematical model of the North Sea is being prepared. Like the electronic analogue model, this project offers a real hope of reproducing the various phenomena observed on the East Coast, and ultimately of providing a valuable means of forecasting surges, including their propagation into estuaries such as the Thames.

51. One of the problems related to research on storm surges which has been investigated by the National Institute of Oceanography is the differences of mean sea level which occur between one part of the sea and another. The difference in level across the Strait of Dover is a question of some practical importance, and a theoretical study has been made of the probable accuracy with which the slope of the mean water surface across the Strait could be calculated from information about the currents, tides, winds and air pressure gradients. It was shown that the effect of the earth's rotation on the residual, non-tidal current through the Strait would be the largest factor, and thus estimated the difference in level between the two sides could be determined to within 3 cm. Optical or radar methods used to compare land levels across the Strait could not be expected to give an accuracy better than half a metre. The preliminary estimate was confirmed by a thorough practical and theoretical study which involved the making of some six-thousand current measurements in the Strait and extensive co-operation from the Hydrographic Department of the Admiralty, Messrs. Kelvin Hughes Limited, and the Chief Engineer of the Post Office. The results indicate that the datum used in France, based on sea level at Marseilles, is approximately 13 cm. higher than the British datum based on sea level at Newlyn.

52. A fortunate concurrence of experimental and theoretical work on the transport of water and energy by sea waves has shown within the past year or two that unexpected changes in mean water level occur when waves approach a coast. If the waves are small and the sea bottom slopes steeply, the water level near the beach is likely to be somewhat lower than it is say half a mile off-shore. But when larger waves run up a gentle slope and lose a lot of energy by breaking, the water level close to the beach will rise, and it appears that the rise may amount to as much as 3 ft. in moderately severe storm conditions. The basic work involved in these studies

may explain some of the differences in mean sea level along our own coast revealed by accurate land levelling. It is of practical importance in assessing the probable effect of waves at high surge levels, and probably quite essential to better understanding of movements of water and sediment close inshore, and thus to all aspects of coastal and harbour engineering.

J. PROUDMAN

(Chairman)

G. J. HILL

(Secretary)

September, 1962.

APPENDIX 1

Membership of the Advisory Committee on Oceanographic and Meteorological Research

1. The first members of the Committee were as shown below. Where there have been changes in offices, honours, etc., since 1954, the list shows the latest position. Present members are marked *

* Professor J. Proudman, C.B.E., M.A., D.Sc., Ll.D., F.R.S., (Chairman)

* Dr. G. E. R. Deacon, C.B.E., D.Sc., F.R.S.E., F.R.S., F.R.G.S., Director of the National Institute of Oceanography.

Dr. A. T. Doodson, C.B.E., D.Sc., Hon. F.R.S.E., F.R.S., Formerly Director of the Liverpool Observatory and Tidal Institute.

Sir Claude Inglis, C.I.E., M.A.I., M.I.C.E., M.I.W.E., F.R.S., Formerly Director of the Hydraulics Research Station, Department of Scientific and Industrial Research.

* Mr. E. A. G. Johnson, C.B.E., B.Sc., M.I.C.E., M.I.W.E., A.M.I. Mun.E., Chief Land Drainage and Water Supply Engineer, Ministry of Agriculture, Fisheries and Food.

* Mr. A. A. L. Lane, B.Sc., M.I.C.E., Deputy Chief Engineer, Ministry of Housing and Local Government.

Mr. R. E. O'Malley, B.Sc., A.M.I.C.E., Formerly Harbour Engineer, Ministry of Transport.

* Dr. R. C. Sutcliffe, C.B., O.B.E., B.Sc., Ph.D., F.R.S., Director (Research), Meteorological Office.

Instructor Commander C.T. Suthons, B.A., R.N., (Retired), Royal Naval Scientific Service, Hydrographic Department, Admiralty.

2. Following the death of Mr. O'Malley in August, 1956, his place was taken for a few months by Lt. Col. C. Le. B. Daman. Since March, 1957, the Ministry of Transport has been represented on the Committee by Mr. S. B. Thomas, B.Sc., A.M.I.C.E., Harbour Engineer.

3. In May, 1957, Mr. R. C. H. Russell, M.A., A.M.I. Mech. E., succeeded Sir Claude Inglis as the representative of the Hydraulics Research Station on the Committee.

4. In June, 1958, the Ordnance Survey was invited to nominate a member to serve on the Committee to assist on work relating to mean sea level. Colonel D. I. Burnett, O.B.E., Deputy Director, Geodetic Control, Ordnance Survey, served until May, 1959, when he was succeeded by Lt. Col. P. J. Carmody, R.E., who was in turn succeeded in May, 1962, by Lt. Col. C. R. Bourne, B.A., R.E.

5. Dr. Doodson retired from the Directorship of the Liverpool Observatory and Tidal Institute and resigned from the Committee in September, 1960. His place was teken by Dr. J. R. Rossiter, D.Sc. (As a result of reorganisation, the work of the Liverpool Observatory and Tidal Institute was taken over by the University of Liverpool, Tidal Institute and Observatory in November, 1960.)

6. In September, 1961, Commander Suthons relinquished his duties in connection with flood warnings and was succeeded as Head of the Flood Warning Organisation and on the Committee by Commander J. N. N. Synnott, D.S.C., R.N. (Retired).

APPENDIX 2

Researches recommended in the Waverley Report

(i) The analysis of tidal records for those stations at which hourly readings are required for the warning system.

(ii) The search for empirical formulae by which surges at Leith, Tyne Entrance, Immingham, King's Lynn, Lowestoft, Harwich and Southend can be predicted as far in advance as possible.

(iii) Investigations on the surge oscillations which occur at Leith, Tyne Entrance, Immingham, King's Lynn, Harwich, Southend and Dover with a view to finding their relationship to the time and height of the maximum surge.

(iv) A study of the interaction between the tide and the surge.

(v) The search for formulae which will enable external surges as recorded at Aberdeen, to be forecast from meteorological data.

(vi) The carrying out of studies like those already carried out for the surges of the North Sea, on surges in the English Channel, the Bristol Channel and the Irish Sea.

(vii) The nature, extent and rate of response of the sea surface to winds of different intensity, duration and fetch and the modification of long waves and surges in shallow water.

(viii) A study of the free and forced oscillations possible in the North Sea.

APPENDIX 3

Grants paid by the Ministry of Agriculture, Fisheries and Food for Research Work on behalf of the Advisory Committee on Oceanographic and Meteorological Research

Financial year to 31st March	*National Institute of Oceanography*	*Liverpool Observatory and Tidal Institute up to 1960/61 (now University of Liverpool Tidal Institute and Observatory)*
	£	£
1954/55		1,850
1955/56	2,500	1,150
1956/57	2,500	2,403
1957/58	2,500	1,073
1958/59	2,500	1,489
1959/60	2,500	1,660
1960/61	2,500	2,040
1961/62	3,500	1,247
	18,500	12,912

APPENDIX 4

Provision of Tide Gauges for Oceanographic Research

1. Ports where tide gauges were already installed in 1953; some of these installations were strategically or operationally inadequate, and have been replaced or added to as indicated below:

Aberdeen
Leith and other North stations
Blyth
Tyne Entrance and Newcastle
Hartlepool, Tees Entrance and Middlesbrough
Immingham and other Humber stations
King's Lynn
Wells
Great Yarmouth
Felixstowe
Southend, Sheerness and other Thames stations
Rochester and Chatham
Ramsgate
Dover
Newhaven
Shoreham
Portsmouth
Southampton
Calshot
Poole
Weymouth
Devonport
Newlyn
St. Helier
Avonmouth
Newport
Milford Haven
Holyhead
Liverpool and other Mersey stations
Preston
Fleetwood
Douglas (Isle of Man)
Dublin
Belfast
Irvine
Gourock and other Clyde stations

2. Ports where new tide gauges have been installed with dates of completion:-

Invergordon	February 1959
Leith	January 1954
Scarborough	January 1958
Immingham	November 1954
Lowestoft	June 1955
Harwich	October 1953
Portsmouth	April 1961
Portland	July 1961
Devonport	July 1961
Swansea	August 1959
Fishguard	November 1958
Holyhead	May 1959
Heysham	June 1958
Larne	March 1957

3. Ports where tide gauges are to be installed:-

Lerwick
Scrabster
St. Mary's (Scillies)
Ilfracombe
Workington
Portpatrick
Tobermory
Ullapool
Stornoway